ARPA ORDER NO.: 189-1
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July 1973

The Black Cloud Experiment

Anne B. Kahle and D. Deirmendjian

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

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Rand
SANTA MONICA, CA. 90406

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PREFACE

There is increasing recognition of the need to investigate the possible climatic effects produced by changes in atmospheric turbidity and in the magnitude of solar radiation reaching the earth. This report describes and assesses the results of an initial simple experiment to simulate these changes with the Mintz-Arakawa numerical atmospheric model.

The work is part of a series of studies undertaken under Rand's Climate Dynamics Program, sponsored by the Defense Advanced Research Projects Agency. For related work, see Rand publications R-877-ARPA, *A Documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model* [W. L. Gates et al., 1971]; R-886-ARPA, *Global Turbidity Studies. I. Volcanic Dust Effects—A Critical Survey* [D. Deirmendjian, 1971]; and R-908-ARPA, *An Experiment on the Sensitivity of a Global Circulation Model: Studies in Climate Dynamics for Environmental Security* [M. Warshaw and R. R. Rapp, 1972].

SUMMARY

The Rand version of the Mintz-Arakawa two-level general circulation model of the atmosphere was used to study some of the effects of a reduction in the incoming solar radiation. The experiment simulated the presence above the atmosphere of a "black cloud" of uniform optical thickness of about 0.10, which reduces the incoming radiation uniformly by 6.5 percent. The main interest in the experiment is in the understanding of the dynamics of the atmospheric response to this reduction. Like other numerical simulation models of the atmosphere, the Mintz-Arakawa model does not at present include turbidity effects. The black cloud experiment may thus also serve to simulate first-order turbidity effects.

The experiment was run for sixty days, and compared with a sixty-day control run. While at first both levels of the atmosphere show a fairly rapid drop in both temperature and wind, after about thirty days the drop in the lower level temperature slows or even stops. This we attribute to a retarding effect due to the release of latent heat in the lower level. This is enhanced as the upper level continues to cool radiatively, causing a steeper lapse rate and more convection, and hence more rainfall and subsequent release of latent heat. Part of the reduced rate of cooling is due to the assumption of a fixed ocean temperature. The total kinetic energy and the total latent energy of the model also decreased from the outset. Although there is some reduction in the rate of decrease of all these quantities by the end of sixty days, the model still appears to be quite far from a new equilibrium state. The rate of decrease of temperature is somewhat slower than has been found by other authors using purely radiation models or radiation-moisture models. This slower response of the Mintz-Arakawa model may be ascribed to the redistribution of part of the energy loss to the kinetic and latent forms, a process which was not possible in the other models.

The present black cloud experiment should be considered as only a first attempt at experiments involving the impact of radiation changes on the climate, and its interpretation must be of a tentative nature until more sophisticated models and analyses can be used. Its results, however, do provide us with guidelines and experience for further experiments involving radiation changes, in which we hope to look at detailed radiation, energy, and moisture balances on a global and regional basis, and to include interactions with the ocean. This, in turn, should lead to a better insight into the physical processes involved in climatic changes.

ACKNOWLEDGMENTS

The authors would like to thank Drs. R. R. Rapp and E. S. Batten for helpful suggestions, and for carefully reviewing and commenting on the manuscript.

CONTENTS

I. INTRODUCTION

"And what will the effect of radiation be?" "We don't know," said Weichert. "It'll have to be calculated." . . . "Can calculate," affirmed Alexandrov. "Will be bloody great calculation."

—FRED HOYLE, *The Black Cloud*

Recently there has been an increasing interest in the possible climatic effects of long-term variations in atmospheric particulate turbidity due to natural causes and/or human activity [SCEP, 1970; SMIC, 1971]. With the advent of various numerical models simulating weather and climate, there is also a demand for the introduction of turbidity in some form into the simulation programs to get an idea of their response and possible climatological implications. The purpose of this report is to describe and discuss a first attempt in this direction.

To begin with, it should be noted that the numerical weather simulation models including the Mintz-Arakawa model (as adapted to Rand's needs) [Gates et al., 1971] do not include turbidity either as a constant or variable parameter. This is understandable in view of the original conception of these *general circulation* models and the difficulties in incorporating the turbidity-related radiation problems in a meaningful and practical manner [Möller and Rodgers, 1970; ARWG, 1972].

A second consideration, quite apart from the above, is the difficulty in obtaining complete solutions to the theoretical radiative transfer problem in a manner to reveal the effect of various types, amounts, and distributions of particulates on the radiation balance at the boundaries and at various levels within the atmosphere. The assumption of a global uniform turbidity involved in some of the climatological conjectures is rather unrealistic, because of the many meteorological factors which would intervene to destroy any uniformity.

For these reasons, as an initial experiment, we have tried what we call a *black cloud* concept [Deirmendjian, 1971], which is attractive both for its simplicity and for its clear physical meaning. The name "black cloud," by the way, was inspired by Fred Hoyle's fascinating story of the same name [Hoyle, 1957], particularly his provocative description of the supposed sequence of meteorological effects produced by an advancing cloud of opaque material which eventually completely envelops the earth. Since in our model (see Sec. II below) only part of the extraterrestial solar flux is reduced by a small percentage, our black cloud experiment may be thought to simulate Hoyle's cloud in its earlier stage when it is interposed in space between the earth and the sun.

More realistically, however, our experiment simulated a specific and plausible condition, namely, that of a true reduction in the solar constant. Interest in the effects of changes in solar constant has been revived in the recent literature [Eriksson, 1968; Sellers, 1969; Budyko, 1972]. In this sense, the results of our present and future black cloud type experiments will contribute not only to our understanding of climatic fluctuations but also to the testing of various conjectures put forward in the literature and to the comparison of results obtained through different climatic simulation models.

Lastly, in a certain sense, the present black cloud experiment may be considered as a first-order approximation to a turbidity experiment [Deirmendjian, 1971]. One would have to assume a turbid layer superposed on the "top" of the model atmosphere such that

- There is a constant absorption over a wide spectral range.
- There is virtually no re-emission of the absorbed energy.
- The amount of absorption is independent of the local solar zenith distance.

Although all three conditions may hardly be realized simultaneously in nature, it is not inconceivable that some types of aerosol may exist which *effectively* approach such conditions as far as the radiation arriving at the earth's surface is concerned.

As already mentioned, however, a correct estimate of radiation fluxes at the earth's surface in terms of various types and amounts of turbidity requires the availability of a complete set of solutions to the planetary radiative transfer problem for various cases of anisotropic, nonconservative scattering in inhomogeneous atmospheres. Knowledge of these solutions would make it possible for turbidity effects to be introduced more realistically into the general circulation model, at the cost of some additional complexity and computing time. Comparison with the simple black cloud results will then be useful in deciding how much the turbidity terms may be simplified without sacrificing scientific soundness.

In what follows we shall describe salient features of the initial response of the Rand version of the Mintz-Arakawa model to the black cloud with the understanding that any interpretations are tentative and subject to future amendment, because we consider that the existing scheme of accounting for radiation effects in the model needs to be improved. We have already initiated some efforts in this direction; but, in the meantime, we believe that the present black cloud results will be of some use in testing the existing model's potentialities and shortcomings in this area.

II. DESCRIPTION OF THE EXPERIMENT

The Mintz-Arakawa model divides the incoming solar radiation into two parts according to the main types of interaction with the atmosphere. The long-wave part, with $\lambda \geq .9\mu$, which is equal to 34.9 percent of the incoming radiation, is assumed to be subject to absorption only. The remaining 65.1 percent of the radiation, the short-wave part with $\lambda < .9\mu$, is assumed to interact with the atmosphere via Rayleigh scattering exclusively. Only this short-wave radiation is allowed to be affected by the black cloud. The insertion of the cloud is accomplished by simply reducing this part by 10 percent, for a net reduction of the incoming radiation by 6.5 percent regardless of the sun's local zenith angle. This is equivalent to assigning a uniform optical thickness of about 0.10 to the Hoyle black cloud, mentioned in the introduction [see also Deirmendjian, 1971, p. 53].

The experiment consisted of running the Mintz-Arakawa model for sixty simulated days, December 31–February 28, with this reduced solar radiation. The Mintz-Arakawa model divides the atmosphere below 200 mb into two layers of equal pressure thickness. The state variables are carried at the center of each of these layers, called level 1 (approximately 400 mb) and level 3 (approximately 800 mb). The temperature and wind velocity components at both levels and the surface pressure and atmospheric moisture (in the form of the lower level mixing ratio) are computed every six minutes and saved every six hours. The ground wetness and ground temperature are computed every thirty minutes and saved every six hours. From these quantities, other variables such as relative humidity, rainfall, evaporation, and long-wave radiation can be calculated. These data are to be compared with data from the "control" run, the same sixty-day period with the same initial conditions, with normal solar radiation. By looking primarily at differences between the black cloud experiment and the control run we remove systematic variations such as the seasonal changes.

To be used for comparison we also have two "perturbation" runs. These consist of the same sixty days with normal solar radiation but with slightly changed initial conditions, achieved by introducing randomly generated noise into the starting values of the temperature at each grid point at the two levels. This noise was randomly selected from a sample with zero mean and a variance of 1°C [Warshaw and Rapp, 1972]. These perturbation experiments are of value in indicating how much of any change noted can be ascribed to the black cloud, and how much is due to the normal variability of the model and the real atmosphere.

III. MAIN RESULTS

TEMPERATURE

The most noticeable change between the control run and the black cloud experiment is a drop in temperature at the ground and in both levels of the atmosphere. Figure 1 shows the zonal averages of the difference in temperature at the upper level of the atmosphere between the black cloud experiment (No. 9) and the control experiment (No. 1), averaged over the second thirty days of the experiment (days 31–60). Figures 2 and 3 show the differences of the same quantities between the perturbation experiments (Nos. 5 and 3, respectively) and the control. The numerical values of the differences of the global averages of temperature for both levels of the atmosphere and ground temperature are in Table 1, along with the same quantities from the first thirty days of the experiments.

It is immediately apparent that, in all the experiments, there is a much greater random variability in the higher latitudes. Also apparent is the drop in temperature in the lower latitudes in the black cloud experiment, as compared with the perturbation experiments. In the global averages (Table 1) there is a substantial drop in temperature (ranging from −.226°C to −.675°C) in the black cloud experiment at all three levels and both time periods, while there are smaller random changes of both signs in the perturbation experiments.

A simple analysis was made to determine the significance of the differences plotted in Figs. 1 through 3. In Fig. 4 we show the result. The dashed curves represent two standard deviations of the temperatures in experiments 1, 3, and 5. The solid curve is the difference between the temperature of the black cloud experiment and the mean temperature of the other experiments. This figure clearly shows that the temperature drop in the black cloud experiment in low latitudes far exceeds any random deviation, while the significance of the high latitude temperature change is unclear.

Because of this rather erratic behavior of the high latitude values, we have defined a "semi-global" average, consisting of the average over one-half the globe by area, lying between +30° (north) and −30° (south) latitude. The time-history of this semi-global average of the temperature differences during the experimental period can be seen in Figs. 5 and 6, which show the instantaneous value of the change in temperatures at the two atmospheric levels and the ground temperature, plotted once a day. The difference of the black cloud experiment from the control is shown in Fig. 5, and the perturbation experiment 5 minus the control in Fig. 6.

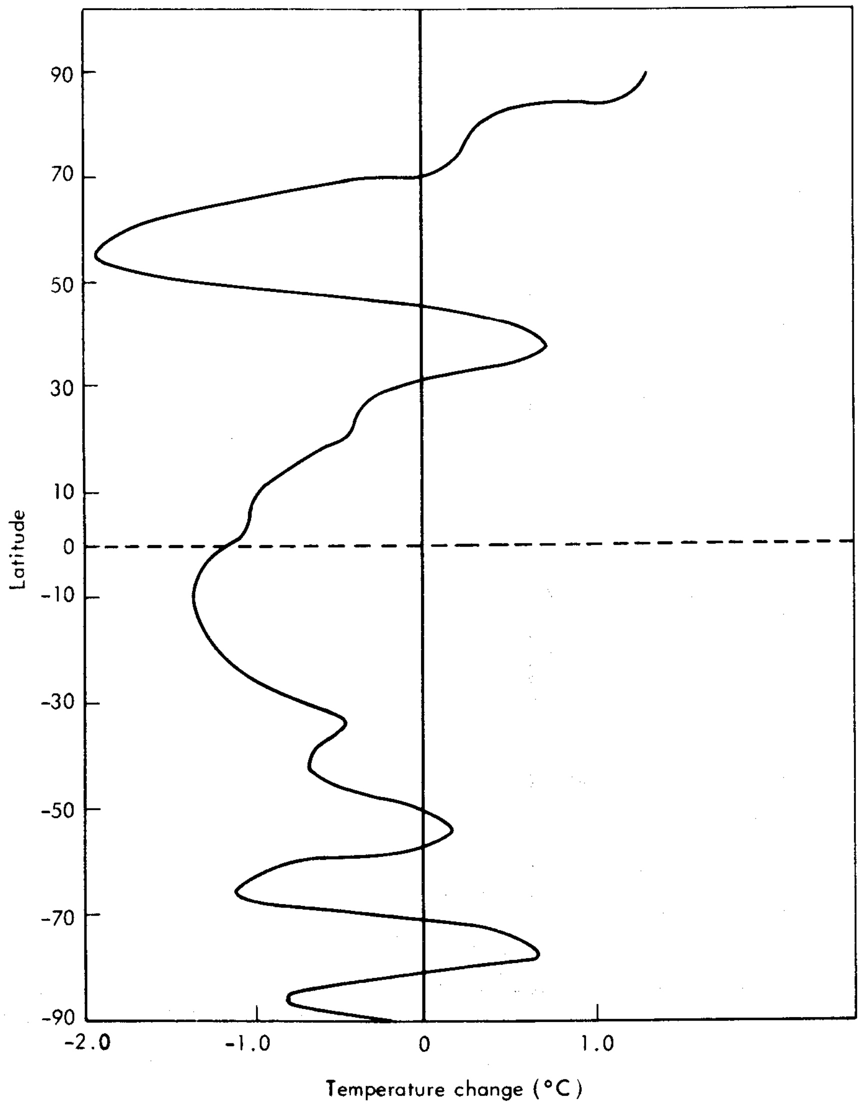

Fig. 1—Zonal average of upper level temperature difference, experiment 9 (black cloud) minus experiment 1 (control), average for days 31-60

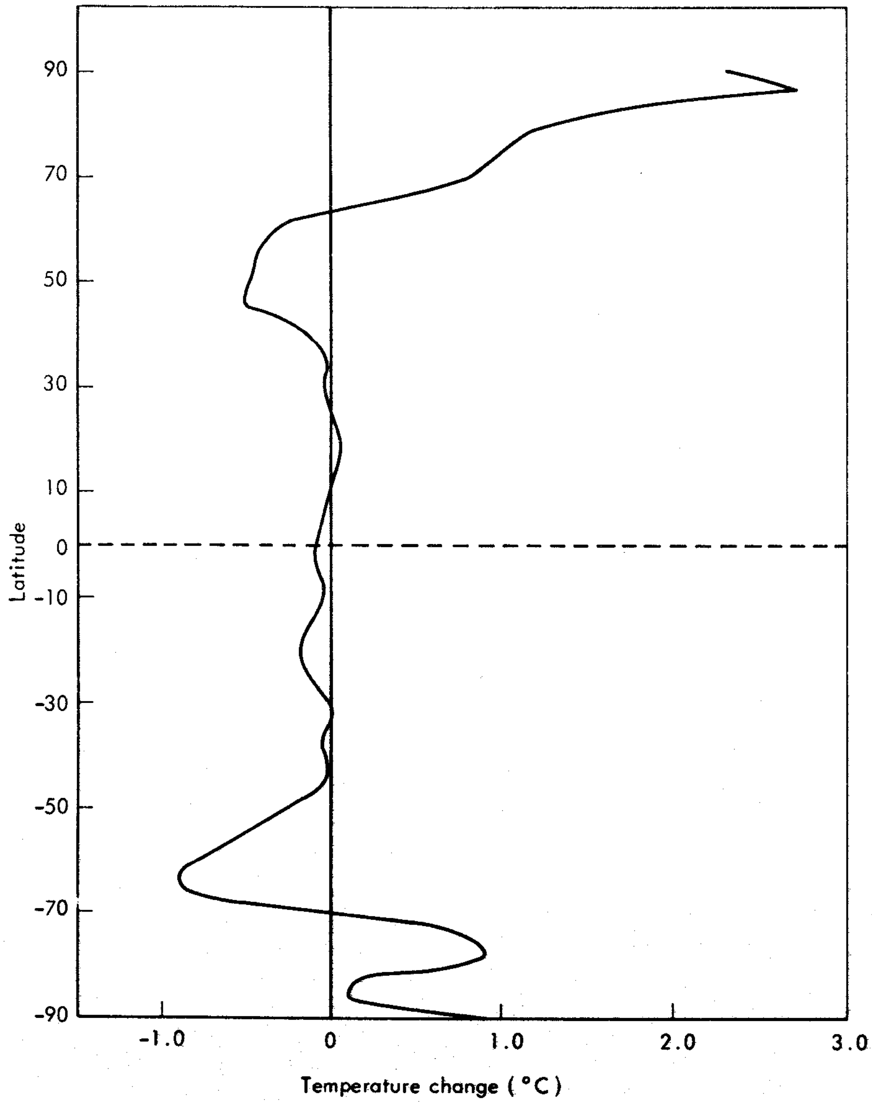

Fig. 2—Zonal average of upper level temperature difference, experiment 5 (perturbation) minus experiment 1 (control), average for days 31-60

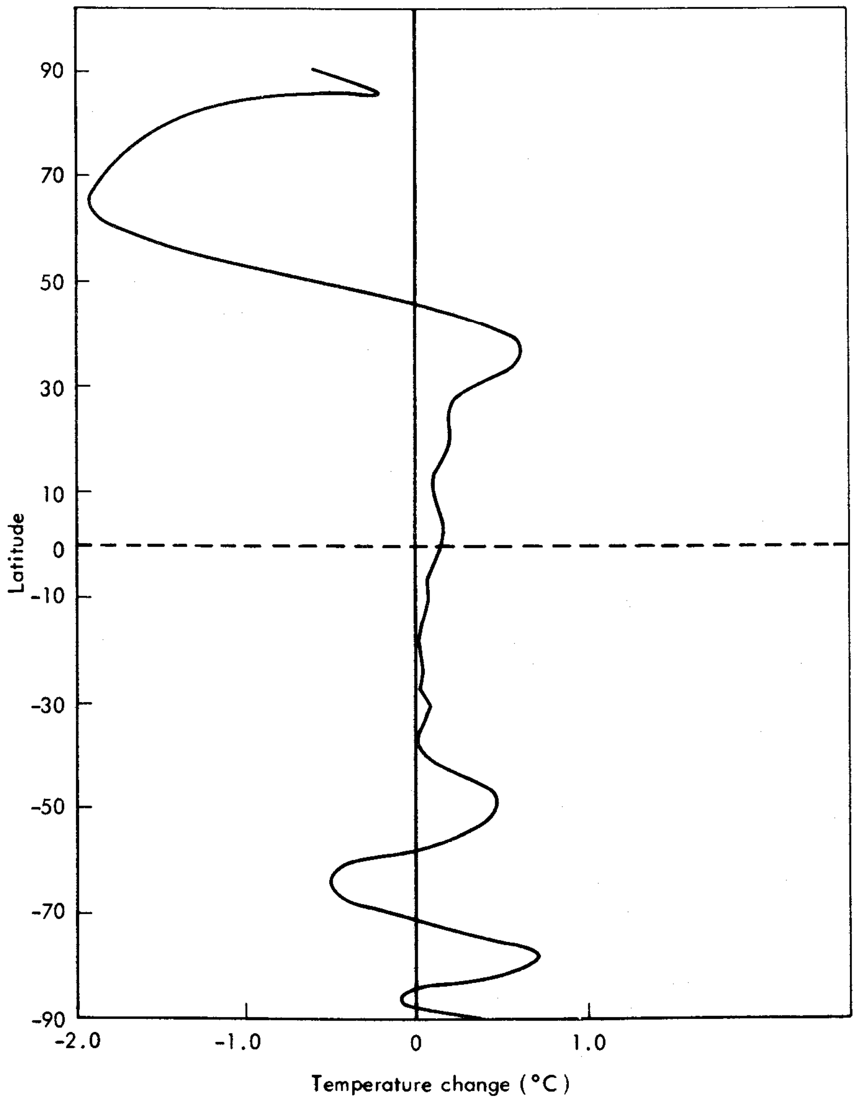

Fig. 3—Zonal average of upper level temperature difference, experiment 3 (perturbation) minus experiment 1 (control), average for days 31-60

Table 1

DIFFERENCES IN GLOBAL 30-DAY AVERAGE OF TEMPERATURE

Days	Experiments: 3 (Perturbation) -1 (Control)	5 (Perturbation) -1 (Control)	9 (Black Cloud) -1 (Control)
	Lower Level Temperature (°C)		
1 - 30	.022	-.101	-.226
31 - 60	.125	.130	-.254
	Upper Level Temperature (°C)		
1 - 30	.084	.063	-.314
31 - 60	-.042	-.073	-.675
	Ground Temperature (°C)		
1 - 30	.060	-.031	-.261
31 - 60	.074	.115	-.374

Under black cloud conditions, the temperature drops quite steadily at all three levels from the very beginning of the experiment. This may be contrasted with the temperature difference curves of the perturbation runs in Fig. 6. We see that the perturbation runs follow the control quite closely for almost two weeks and then diverge from it. This divergence may illustrate the lack of predictability of the atmosphere, as discussed by Lorenz [1969], and, in the context of the Mintz-Arakawa model, by Warshaw and Rapp [1972]. The range of the variations in the perturbation experiment temperature curves is quite similar to those in the black cloud curves, but the perturbation values oscillate approximately around the zero difference curve, while the black cloud oscillations show an increasing negative trend.

The temperature drop in the black cloud experiment is at first about equal for all three levels of the atmosphere. In the second thirty days, while the temperature of the upper level of the atmosphere continues to fall at about the same rate, the lower level atmospheric temperature and ground temperature appear to have stopped decreasing. While this apparent slowing of the temperature drop could be due just to random variations in the temperatures, we feel it is due to some physical process diverting the energy loss to another form. We shall discuss later why we consider that a new equilibrium temperature has not yet been established.

WIND

Another meteorological parameter that shows interesting behavior in the black

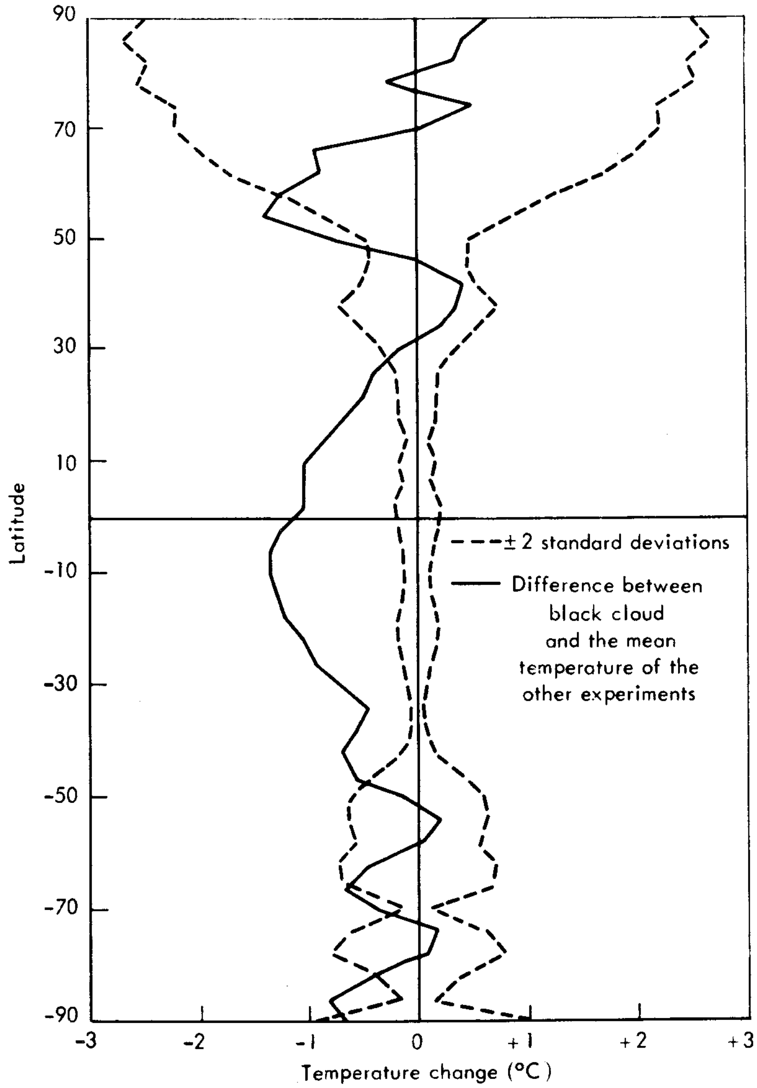

Fig. 4—Comparison of black cloud temperature difference with deviations from the mean upper level temperature of experiments 1, 3, and 5, average for days 31-60

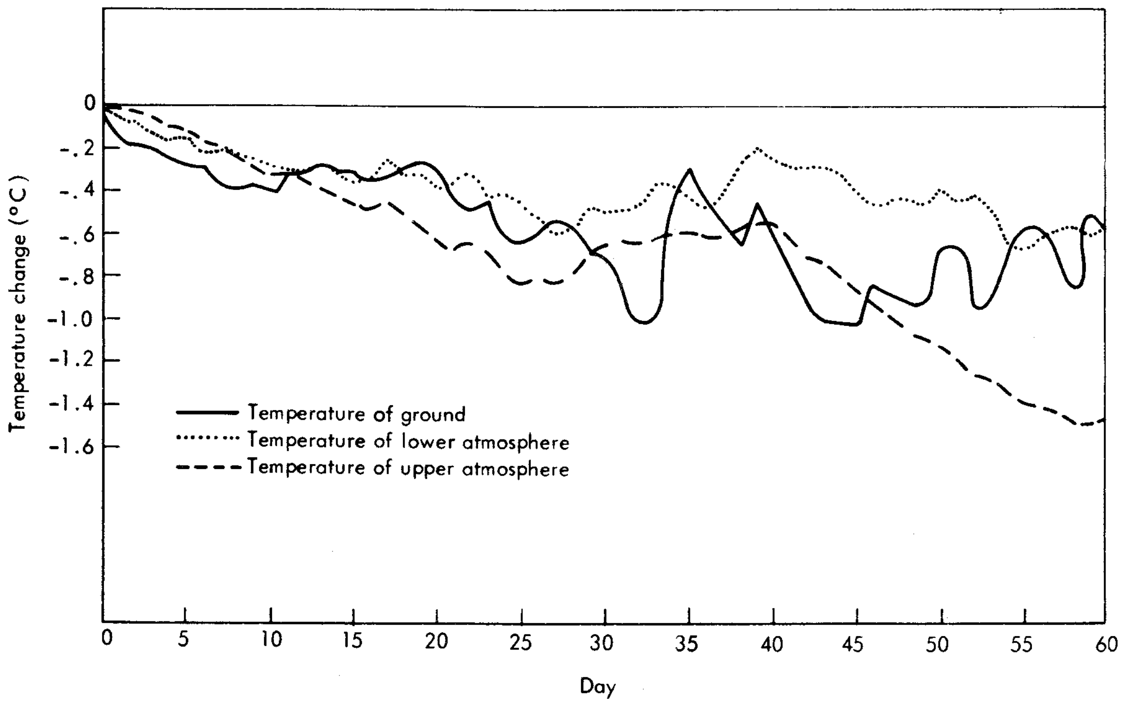

Fig. 5—Change in semi-global average temperature, black cloud experiment minus the control run

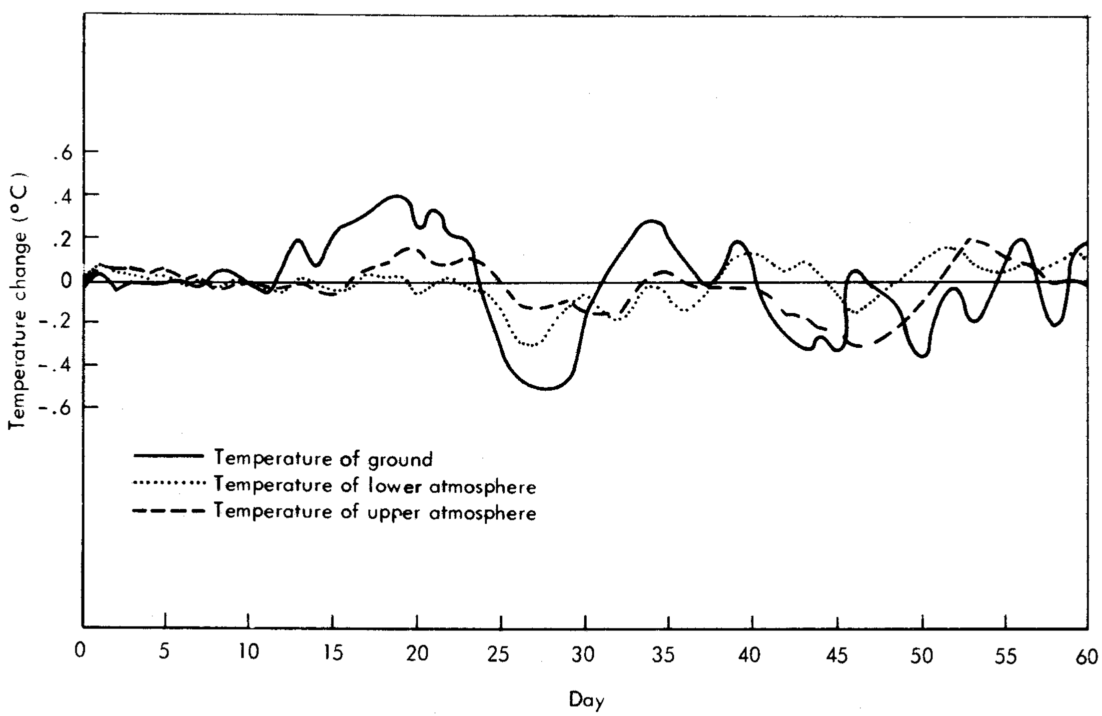

Fig. 6—Change in semi-global average temperature, perturbation experiment 5 minus the control run

cloud experiment is the wind speed. The change in the absolute value of the horizontal component of the wind for level 1 is given by

$$\left[(u_1^2 + v_1^2)^{1/2}\right]_{\exp 9} - \left[(u_1^2 + v_1^2)^{1/2}\right]_{\exp 1}$$

with a similar expression for level 3. The daily values of the semi-global averages of these wind changes are plotted in Fig. 7 for the black cloud and in Fig. 8 for perturbation experiment 5. The global 30-day averages of the wind speed changes are given in Table 2.

Like the temperature, the black cloud winds show an immediate decrease in both levels, with a reduced rate of decrease in the lower atmospheric level during the second thirty days. This drop in wind speed may be ascribed to a conversion of available potential energy to kinetic energy, accompanying the energy loss to the system. The increase in wind back to a positive difference value near the end of the first thirty days appears to be a random perturbation superposed on the dropping values. This is probably a larger than usual variation in the wind in the control run because this particular feature appears in all the differences between experiments, black cloud or perturbations, minus the control run.

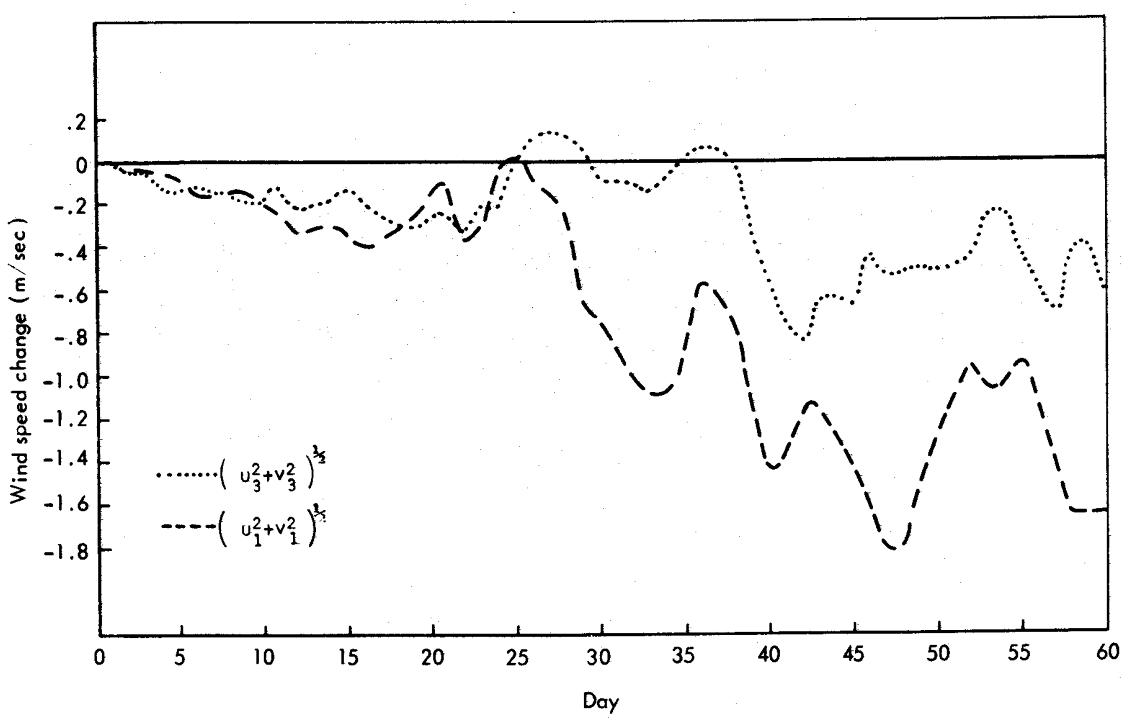

Fig. 7—Change in semi-global average wind speed, black cloud experiment minus the control run

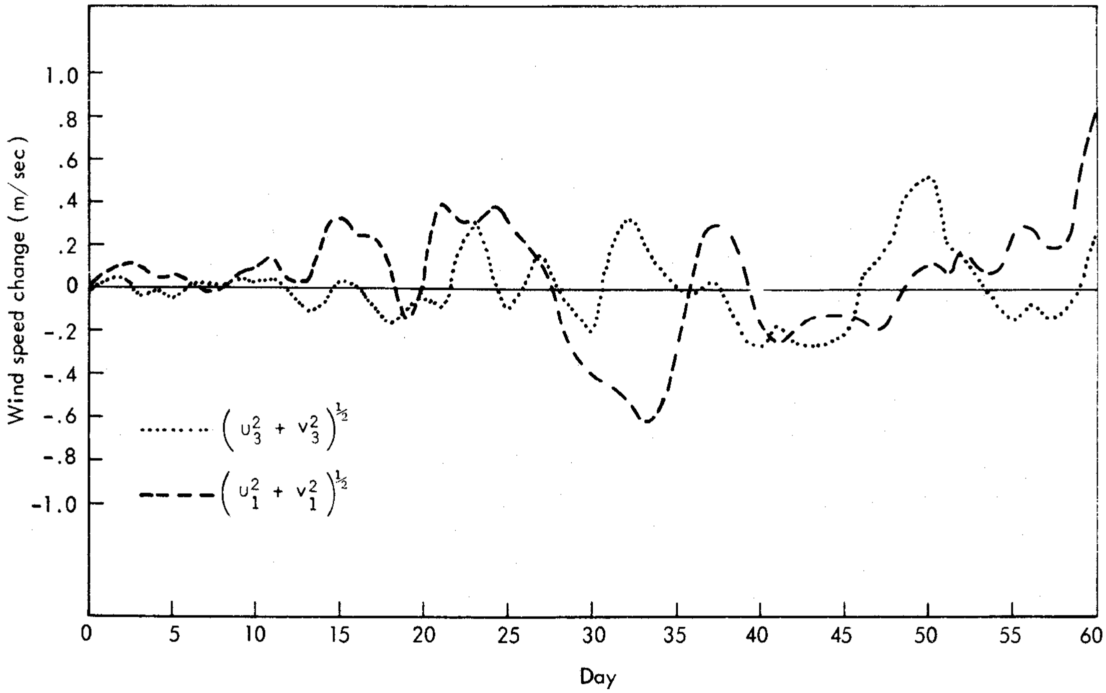

Fig. 8—Change in semi-global average wind speed, perturbation experiment 5 minus the control run

Table 2

DIFFERENCES IN GLOBAL 30-DAY AVERAGE OF WIND SPEED

Days	Experiments		
	3 (Perturbation) -1 (Control)	5 (Perturbation) -1 (Control)	9 (Black Cloud) -1 (Control)
	Upper Level Wind Speed (m/sec)		
1 - 30	.149	.123	-.058
31 - 60	.046	-.004	-.682
	Lower Level Wind Speed (m/sec)		
1 - 30	.061	.032	-.004
31 - 60	.010	.007	-.243

A parameter of some meteorological interest is the eastward (or zonal) component of the wind. Zonal averages of the changes in zonal winds at the lower level averaged over the second thirty days are shown in Fig. 9 for the black cloud experiment, Fig. 10 for perturbation experiment 5, and Fig. 11 for perturbation experiment 3. Again we see the greater variability of the high latitude values. The large oscillation from a high negative value at 35°N to a high positive value at 54°N in both black cloud (Fig. 9) and perturbation 3 (Fig. 11) represents a northward migration of the maximum westerlies in the northern hemisphere from 42° to 46° latitude. These displacements are associated with corresponding changes in the temperature and pressure gradients in both cases. Since this phenomenon is in one of the perturbation runs as well as the black cloud run and also has been seen in some other experiments, it is probably not significant in the black cloud experiment. There is again, however, a net drop in the low latitude wind, which is probably significant. This can be seen better in Fig. 12, showing the development of this drop with time in the semi-global average of the wind difference at both levels. The same curves for perturbation 3 are shown in Fig. 13. Unlike the total wind, the drop in zonal wind does not appear to begin immediately. However, the size of the random variations is such that one cannot unequivocally state when the drop commenced, but only that it appears to be at some later time, on the order of two weeks to a month after the advent of the black cloud.

MOISTURE

Other variables which show a change in the black cloud experiment are those related to moisture, especially in the tropics. The total precipitable water in the atmosphere, the relative humidity, the ground water, and the evaporation are all somewhat lower on a global average. Global averages of the changes in these quantities for the various experiments are listed in Table 3.

One would expect the total water content of the atmosphere to be reduced in the black cloud experiment, since the temperature is lower. The evaporation is lower due to the combined effect of the drop in surface temperature and surface wind. Since the ocean temperature is not allowed to drop, and most evaporation will occur over the ocean, the reduced wind is probably the more important of the two causes. This may be the reason that the evaporation does not vary much during the first thirty days, since the wind has not yet dropped significantly.

A lower evaporation rate might be expected to cause the drop in relative humidity. However, this drop in relative humidity is substantial in the first thirty days, before the evaporation has decreased. More likely, the drop in relative humidity is caused by increased rainfall, produced by increased convective activity due to the upper level of the atmosphere cooling more rapidly than the lower. Unfortunately, this can not be verified because the precipitation data are not reliable, due to a sampling error [Batten et al., 1973].

The time dependence of the semi-global averages of two of the moisture variables, the ground water and the lower level mixing ratio, q_3, are shown in Fig. 14, again illustrating a rather steady decrease, with superimposed oscillations. The decrease in the moisture content of the atmosphere can be regarded as a decrease

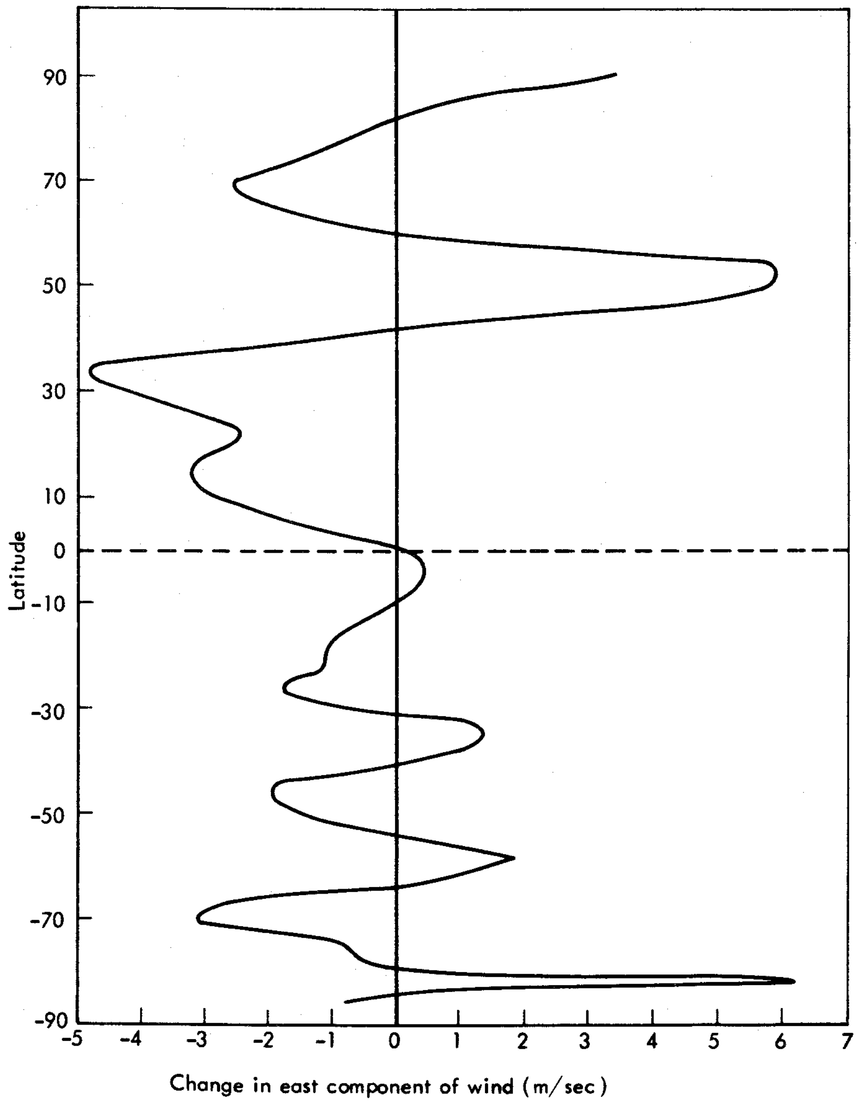

Fig. 9—Zonal average of zonal wind difference, black cloud experiment minus control run, average for days 31-60

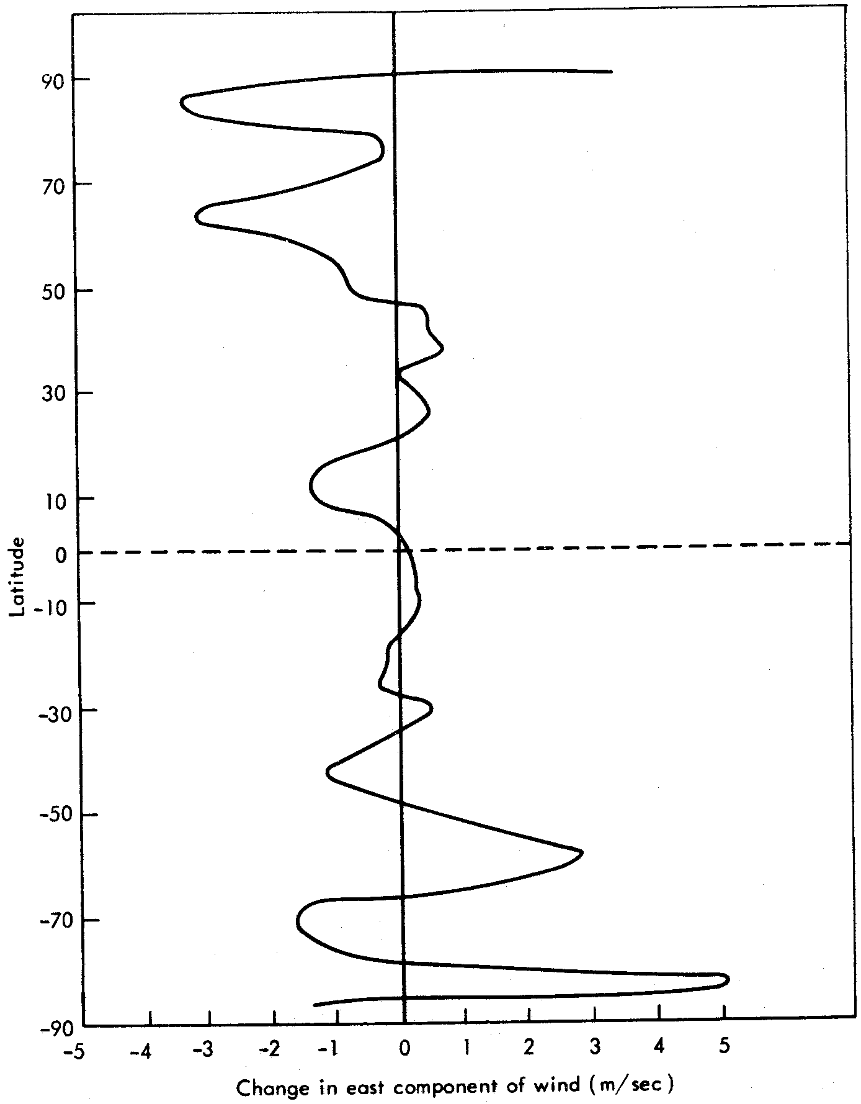

Fig. 10—Zonal average of zonal wind difference, perturbation experiment 5 minus control run, average for days 31-60

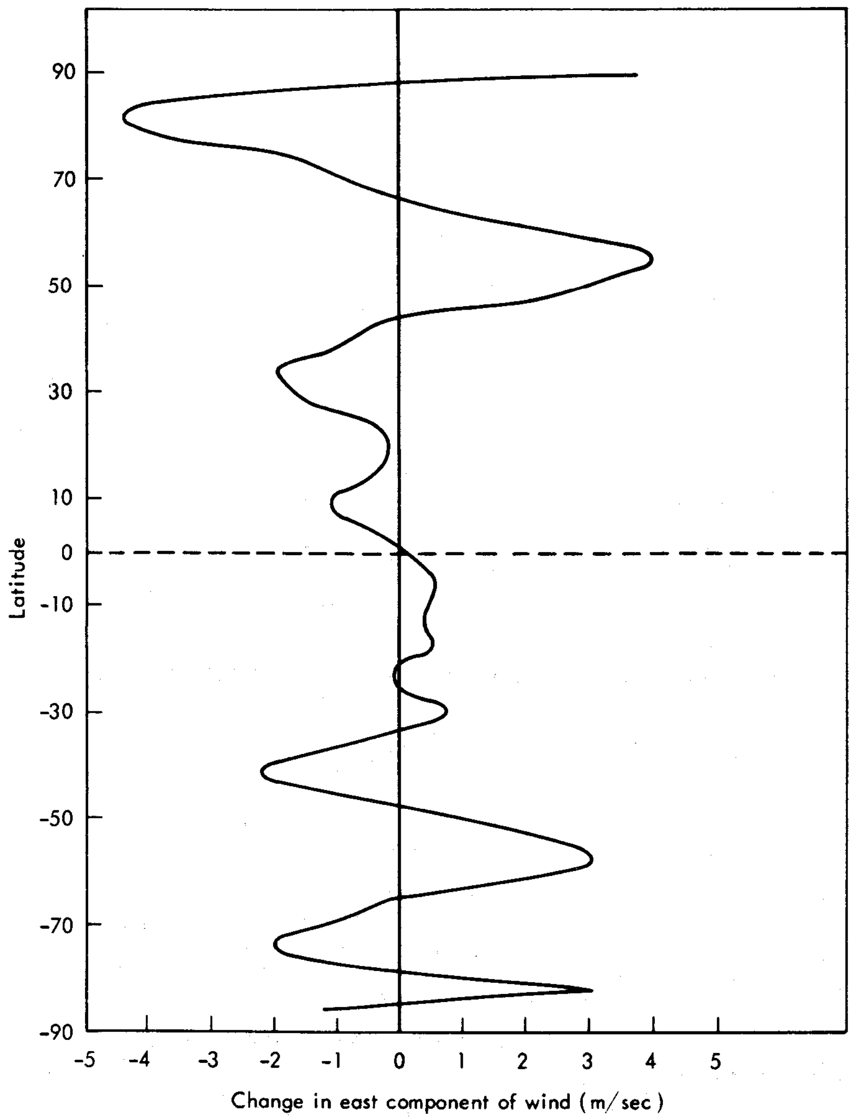

Fig. 11—Zonal average of zonal wind difference, perturbation experiment 3 minus control run, average for days 31-60

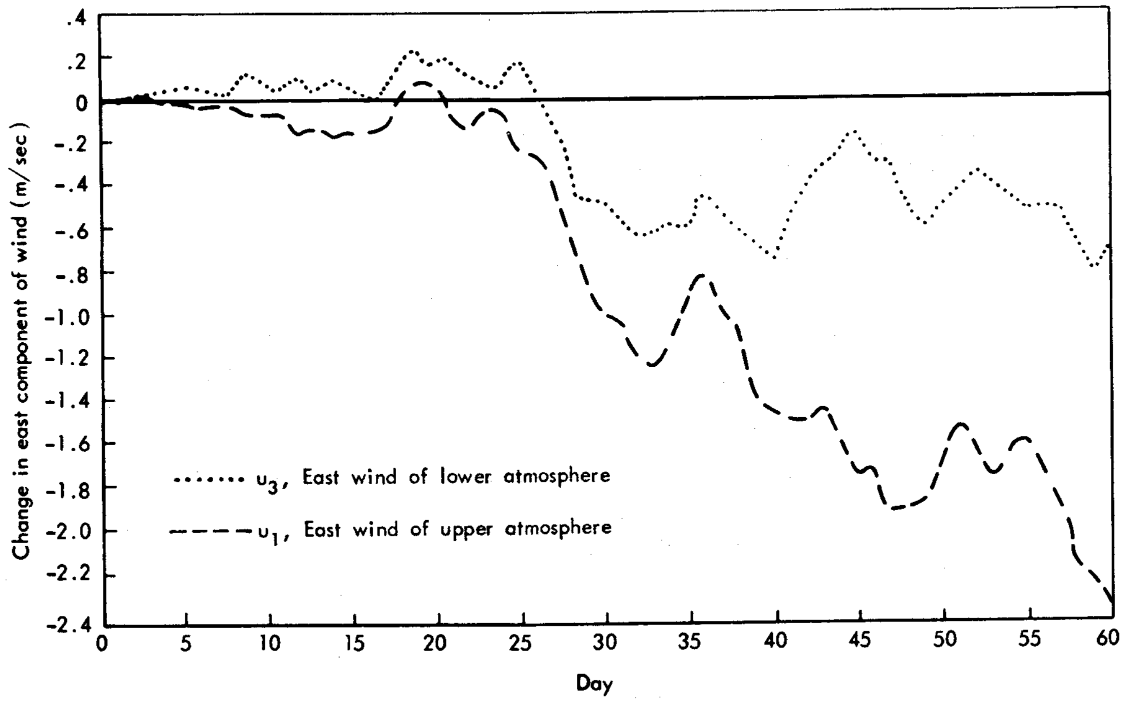

Fig. 12—Change in semi-global average of zonal wind, black cloud experiment minus control run

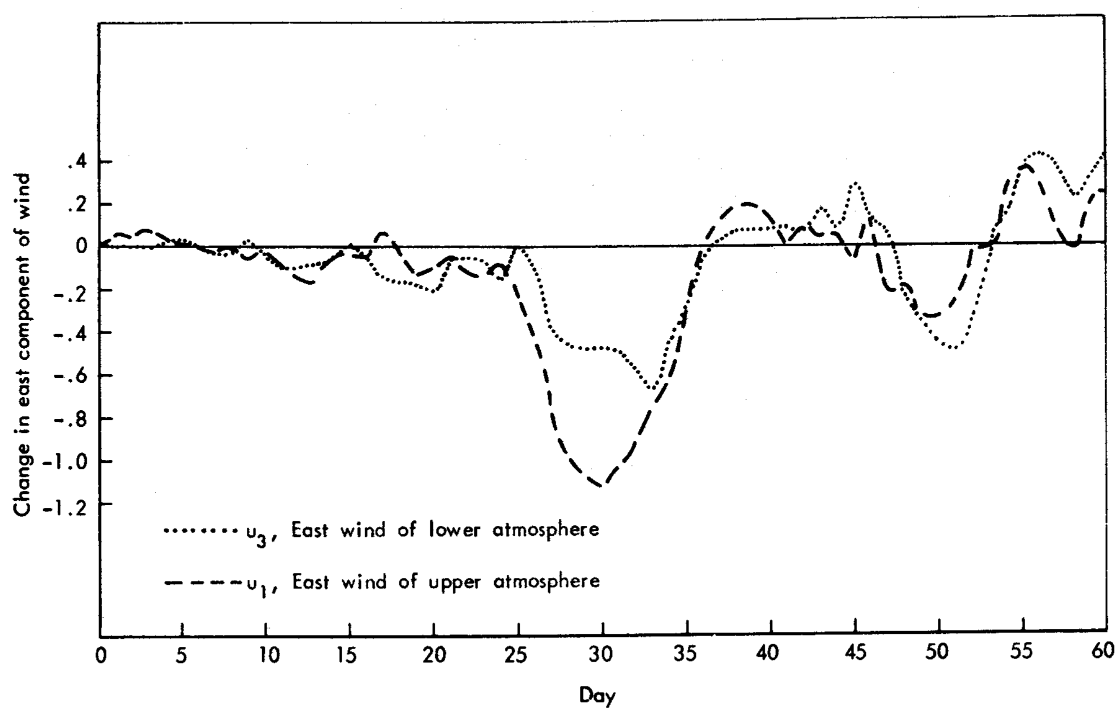

Fig. 13—Change in semi-global average of zonal wind, perturbation experiment 3 minus control run

in the latent form of internal energy. Thus, just as with the kinetic energy, we see an immediate redistribution of the imposed decrease in thermal energy to another form of energy in the system.

Table 3

DIFFERENCES IN GLOBAL 30-DAY AVERAGES OF MOISTURE VARIABLES

Days	Experiments		
	3 (Perturbation) -1 (Control)	5 (Perturbation) -1 (Control)	9 (Black Cloud) -1 (Control)
	Precipitable Water (cm)		
1 - 30	.004	-.008	-.053
31 - 60	.008	-.002	-.079
	Evaporation (mm/day)		
1 - 30	.023	.002	.007
31 - 60	-.038	-.015	-.080
	Ground Water (scaled 0 to 10)		
1 - 30	.001	.000	-.007
31 - 60	-.011	-.011	-.031
	Relative Humidity (percent)		
1 - 30	.060	.018	-.698
31 - 60	-.106	-.221	-.984

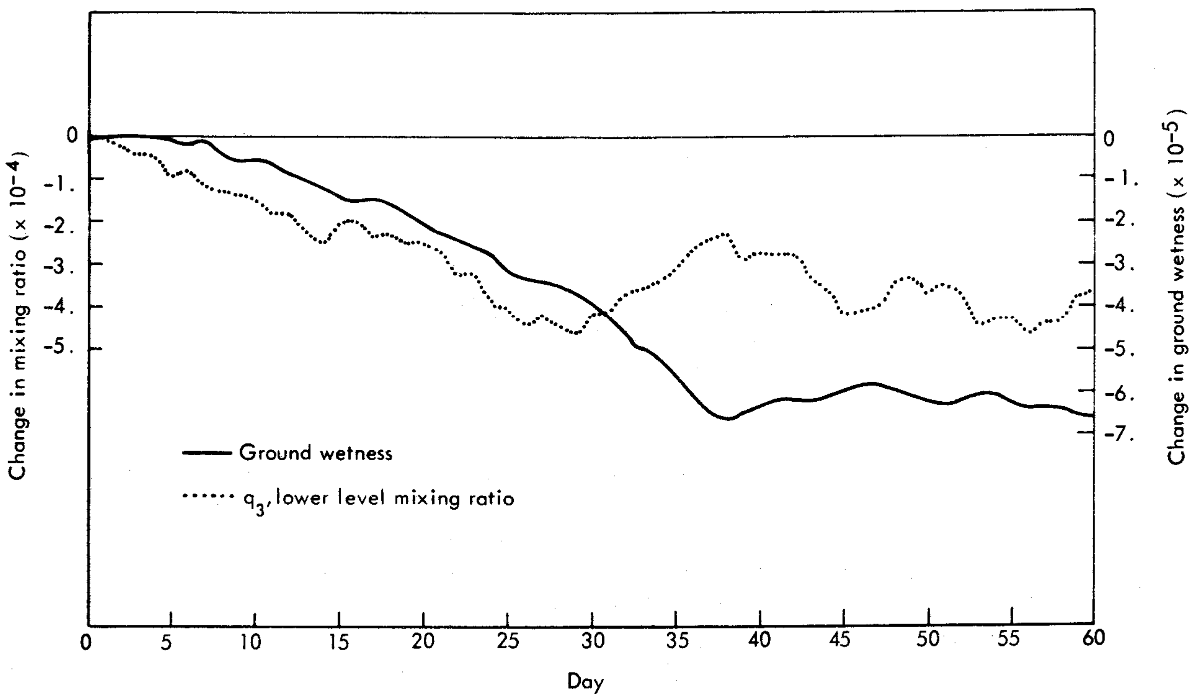

Fig. 14—Change in semi-global average of ground wetness and lower level mixing ratio, black cloud experiment minus control run

IV. COMPARISON WITH OTHER WORK

Although our present results are not definitive, due to the uncertainty in the Mintz-Arakawa scheme mentioned below, it is instructive to compare them with those obtained by other authors. There have been several recent estimates of how much the earth should cool due to a decrease in the solar constant, based on a variety of different assumptions, some theoretical, some empirical (Bernard, 1964; Sheppard, 1964; Rakipova, 1967; Budyko, 1969; Sellers, 1969). Eriksson (1968) has outlined several methods of making such a determination; he finds a range from 0.2° to 2°C per one percent change in solar constant, and postulates that about 1°C per one percent is probably a realistic estimate. This is in fair agreement with or slightly lower than the estimates of most of the others mentioned above.

Thus it would seem likely, with our 6.5 percent reduction in the solar constant, that we might expect a temperature drop of something like 5° to 10°. After 60 days we have seen a drop of only about 0.5°C in the lower atmosphere and 1.5°C in the upper atmosphere. This is one reason leading us to believe that the apparent slowing of the temperature drop at the lower level is not due to a new equilibrium temperature having been reached.

Manabe and Wetherald [1967], following preliminary work of Manabe and Strickler [1964], have also used a numerical model of the atmosphere to investigate, among other things, the length of time for the atmosphere to reach an equilibrium temperature after a substantial temperature perturbation. This problem should be related to the length of time for our model to reach a new equilibrium temperature after the change in solar constant. They have elevated the temperature 15° and determined the rate of return to the unperturbed state. Their experiments have progressed through stages allowing progressively more interaction between the radiation and the hydrological cycle. First they maintained a constant absolute humidity, than a constant relative humidity, and finally they allowed for the release of latent heat implicit in the decreasing moisture content. Each time they increase the interaction, the length of time to approach equilibrium increases.

If we anticipate a total decrease of, say, 5°, and match our Fig. 5 with their Fig. 6, then we find that our approach to equilibrium is roughly two or three times slower than their most interactive model (atmosphere III). This, we assume, is due to our model having complete interaction with the hydrological cycle and also allowing the interaction with the kinetic energy.

Manabe and Wetherald [1967] have also determined the total change in temperature in their model atmosphere due to various changes in the solar constant.

Reading from their Fig. 8, one finds, for a 10 percent decrease in solar constant, a decrease at ground level and at 800 mb of approximately 12°, and a decrease at 400 mb of approximately 10°. These numbers agree well with the various theoretical estimates already mentioned. This is a further indication that we should expect a greater temperature drop than so far attained, and also indicates that perhaps in a new equilibrium state the upper air should have cooled slightly less than the lower. This is just the opposite from what has occurred so far in our model, again suggesting that our experiment is probably far from a new equilibrium state. The slower rate of temperature drop in the lower level is due in part, of course, to the fixed ocean temperature.

V. DISCUSSION

In summary, we have performed an initial "black cloud" experiment by simply reducing the short-wave part (65 percent) of the solar spectrum as specified in the Mintz-Arakawa model by 10 percent. This resulted in significant reductions of the temperature and wind of both atmospheric levels of the model, and in atmospheric moisture.

While at first both levels of the atmosphere show a fairly rapid drop in both temperature and wind, after about thirty days the drop in the temperature of the lower level slows or even stops. This we attribute to a retarding effect due to the release of latent energy in the lower level. This is enhanced as the upper level continues to cool radiatively causing a steeper lapse rate and more convection, and hence more rainfall and subsequent release of latent heat.

Part of the reduced rate of cooling is due to the ocean temperature being fixed. This does not necessarily mean that the ocean continues to pour heat into the atmosphere at an unabated or even accelerated rate, since much of the heat transference is in the form of latent heat. With the reduced evaporation noted, due to decreased wind speed, we expect that there will be a lessening of the upward heat flux from the ocean by this mechanism, although the long-wave radiative and sensible heat fluxes will probably be enhanced. However, these inferences cannot be verified from the available experimental data.

While our experiment is related in some ways to the one performed by Manabe and Wetherald [1967], it goes a step further in that the hydrological cycle is completely integrated into the dynamics of the model. The relative humidity is not constrained to remain constant. In addition, the atmospheric dynamics in our model allow interaction with the wind. Thus much of the energy loss in the system is transformed to a kinetic energy and a latent energy loss. This apparently results in a slower approach to equilibrium than that found by Manabe and Wetherald.

Thus we would expect that it will take many months or even years to reach a new equilibrium in response to any changes due to the black cloud. Even if we were to allow the ocean temperature to drop correspondingly, only a pseudoequilibrium would result, as it might take hundreds of years for the energy stored in the ocean to be depleted to the point of a true new equilibrium (see, for example, Eriksson [1968]).

Budyko has recently [1972] postulated that even a two percent drop in solar constant would change the climate regime sufficiently to create a new ice age, so the whole question of the approach to equilibrium after such a large change may be

rather academic. On the other hand, the slow response time we found for the atmosphere does have implications for the seasonal changes. It is of particular interest in the study of short-lived changes in insolation, such as might be caused by large-scale transient pollution events, man-made or natural.

It should be mentioned that several minor errors in the radiation part of the model have been found since the original run of this black cloud experiment. We also discovered certain limitations in the output routines, e.g., some data were not saved, or sampling errors were significant. Most of these minor problems have been corrected in subsequent control runs and experiments, as described in Batten et al. [1973]. While these were not considered serious enough to substantially affect the results reported here, they did appear to preclude the desirability of more detailed analysis.

The present black cloud experiment should be considered as only a first attempt at experiments involving the impact of radiation changes on the climate, and its interpretation must be of a tentative nature until a more sophisticated analysis can be made. The results, do, however, provide us with guidelines and experience for further experiments in this area, which should include the improved treatment of the physics of the effects of particulates on radiation, mentioned in the introduction. In future experiments involving radiation changes, we also hope to look at detailed radiation, energy, and moisture balances on a global and regional basis, and to include interactions with the ocean. This, we hope, will give us a better insight into the physical processes involved in climatic changes.

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